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## The interaction of radio sources and cooling flows

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**Abstract.** The X-ray emission in many clusters of galaxies shows a central peak in surface brightness coincident with a drop in temperature. These characterize a cooling flow. There is often a radio source also at the centre of such regions. Data from Chandra now enables us to map the interaction between the radio source and the intracluster medium. Preliminary work shows no sign of heating of the gas beyond the radio lobes, which are often devoid of cooler gas and so appear as holes. In the case of the Perseus cluster around 3C84, the coolest X-ray emitting gas occurs immediately around the inner radio lobes.

### 1. Introduction

The X-ray surface brightness continues to rise towards the centre in two thirds of all clusters of galaxies. The radiative cooling time of the gas there continues to decrease, dropping below 10 Gyr at 70–150 kpc and 1 Gyr at 5–30 kpc. The smaller radius values apply to low luminosity clusters such as that in Virgo, the larger ones to the high luminosity ones such as that in Perseus. Within this inner region the gas temperature also drops, from 3–10 keV down to 1–3 keV, as determined by simple single-temperature spectral fits. The gross appearance of these regions fits that of a cooling flow (see Fabian 1994 for a review), in which radiative cooling of the central dense parts of a hydrostatic atmosphere causes it to subsonically slump inward under the influence of gravity and the weight of overlying gas. About 10 per cent of clusters, such as the Coma cluster, do not show the central peak in X-ray emission and have no cooling flow. Another 10–20 per cent of clusters, such as A754, have complex structure, probably due to a cluster-cluster merger.

The inferred rate at which gas is cooling out in cooling flows ranges from  $< 10 M_{\odot} \text{ yr}^{-1}$  in poor clusters to  $> 1000 M_{\odot} \text{ yr}^{-1}$  in massive rich clusters. These values are uncertain and depend on an assumed age for the flow if determined only from x-ray imaging. Only when X-ray spectra show the cooling components can the rate be clearly defined. In that case an estimate for the age of the flow is obtained as well. Work using ROSAT and ASCA data (Allen & Fabian 1997; Allen et al 1999) indicates that the ages may be about 5 Gyr. Many clusters appear to have rates of a few  $100 M_{\odot} \text{ yr}^{-1}$ , which suggests total cooled gas masses of  $10^{11} - 10^{12} M_{\odot}$ . Blue light from massive stars and emission line nebulosities are common in such regions (see Crawford et al 1999 and references therein) but normal star formation accounts for only about 10 per cent of the cooling rate.

What happens to the rest is not clear. It has been suggested that heating balances cooling so that little or no gas actually cools from the X-ray emitting hot gas component (Rosner & Tucker 1989; Binney & Tabor 1995; Soker et al 2000). This seems plausible when it is noted that most cooling flows have a radio source in the host central cluster galaxy. If somehow the accretion power from a small amount of gas accreted onto a central black hole can be distributed into the cooler and cooling gas then perhaps some equilibrium may be obtained. Thermal conduction too must be worried about since we are discussing cooler gas components embedded in hotter ones.

The problem here is that the X-ray data show little sign that the radio sources are actually heating the bulk of the gas. Of course there is something going on in the radio lobes, but these occupy only a small fraction of the flow. What is needed to stem a cooling flow is a lot of energy into the cooler gas. It has to hit the gas with the shortest cooling times. The heating needs to be complete in the sense that it shouldn't just cause the gas to hang up at some temperature below the outer cluster temperature or it would easily be detected. It must also allow gas to cool (or give the appearance of cooling) down to 1–3 keV. This is not trivial.

Here I review the recent results from Chandra which resolve the radio – X-ray interaction regions in some luminous clusters. The simple result is that the coolest gas is seen to be closest to the radio lobes. Not what a heating model would be expected to show if the lobes are responsible for the heating.

## **2. Chandra results**

### **2.1. Hydra A and 3C295**

Early data from Chandra showed clear evidence for ‘holes’ in the X-ray in the vicinity of the radio lobes in the Hydra A cluster (McNamara et al 2000). The central radio source here is fairly powerful and the lobes occupy one of the larger fractions of the cooling region. Later work suggests that a small cooling flow may operate only near the centre of the region (David et al 2000) at a rate compatible with the star formation seen.

The radio lobes in the powerful FR II source 3C295 are seen in X-ray emission, presumable as a consequence of inverse-Compton scattering (Harris et al 2000). The surrounding emission does however appear to be reasonably undisturbed and undergoing a cooling flow (Allen et al 2000).

### **2.2. The Perseus cluster and 3C84**

The core of the Perseus cluster around the central galaxy NGC1275 and its radio source 3C84 has long been known to have X-ray ‘holes’ at the positions of the radio lobes (Bohringer et al 1993). ROSAT data showed good agreement between the holes and inner lobes. Chandra imaging now shows this very clearly (Fabian et al 2000a; Fig. 1).

The exact 3D geometry is not obvious (Fig. 2). Presumably the S jet is pointing toward us at some angle. There are also several outer holes seen (Fabian et al 2000a) which may represent older, buoyant lobes (Churazov et al 2000a). The energetic electrons may now have cooled in these regions but

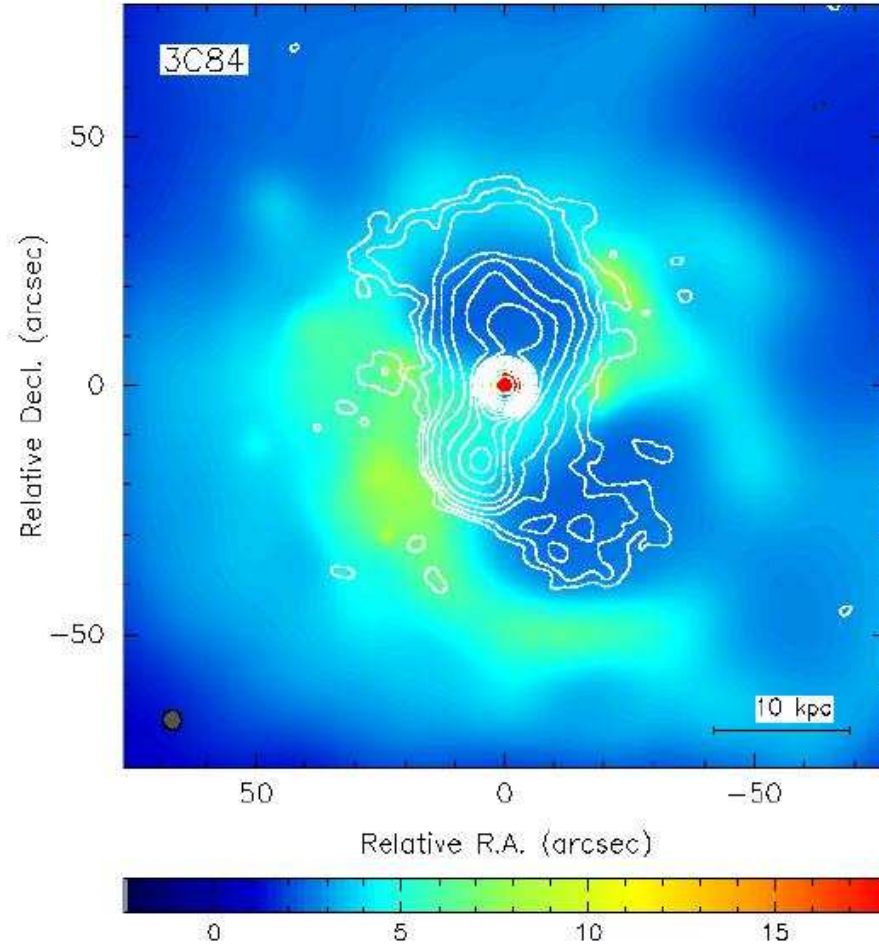


Figure 1. Radio image (1.4 GHz restored with a 5 arcsec beam, produced by G. Taylor; see Fabian et al 2000a) overlaid on adaptively smoothed 0.5–7 keV X-ray map.

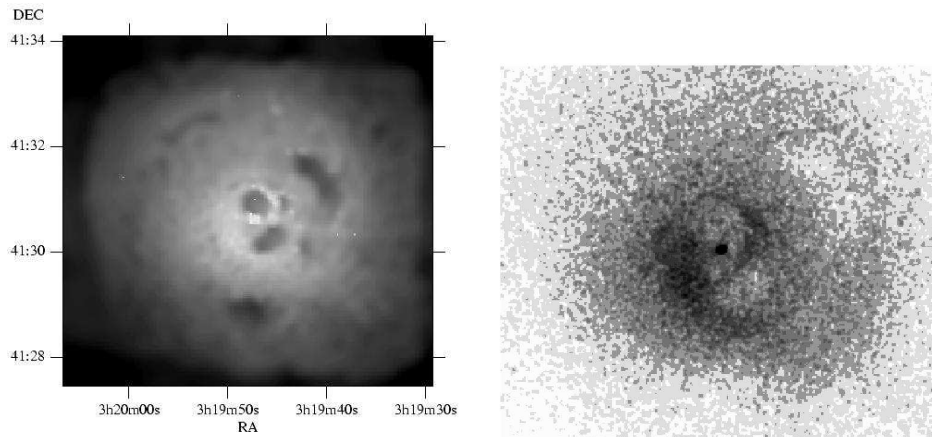


Figure 2. (Left) Adaptively-smoothed 0.5–7 keV ACIS-S X-ray image; (Right) gaussian-smoothed ACIS-I X-ray image of the centre of the Perseus cluster. The ACIS-S image has cosmetic blurring due to a nodal boundary running from just below the nucleus to the W. These effects are absent in the I image. Note that the I image shows better the complex structure of the inner part (compare with Fig. 1). The precise nature of this structure is not clear. The holes may be roughly in the plane of the Sky or, more likely, arranged in a perpendicular sense with the apparent ‘e’ shape being part of a helix oriented along our line of sight.

the nonthermal pressure from the protons, magnetic field and cooled electrons may keep them inflated and less dense than the surroundings. A spur of radio emission toward the W outer hole is seen in the 74 MHz map of Blundell et al (2000) which supports this idea.

The Chandra data (Fabian et al 2000a) covers the 0.3–7 keV range and can be divided into colours from which absorption and temperature maps can be constructed. Significant excess absorption is seen in the region of the ‘high velocity system’, an irregular galaxy falling into the cluster core close to our line of sight. The temperature map (Fig. 3) shows that the gas is cooler toward the centre with the coolest gas along the rims of the inner radio lobes and in the bright E blob. The surface brightness can be used to obtain the gas density and thus pressure and radiative cooling time. The cooling times are also shortest close to the inner radio lobes.

We see no sign that the lobes have heated the gas beyond the lobes. Something has happened within the lobes. They have either been cleared of gas, or perhaps just cleared, of cooler gas. The intracluster medium there may be multiphase with cooler, cooling, blobs embedded within a hotter phase. The lobes may have only pushed aside the cooler blobs. A simple rearrangement of the cooler gas is in agreement with the observed surface brightness excess around the rims of the lobes. There is certainly no sign of the strong shocks suggested by Heinz et al (1998).

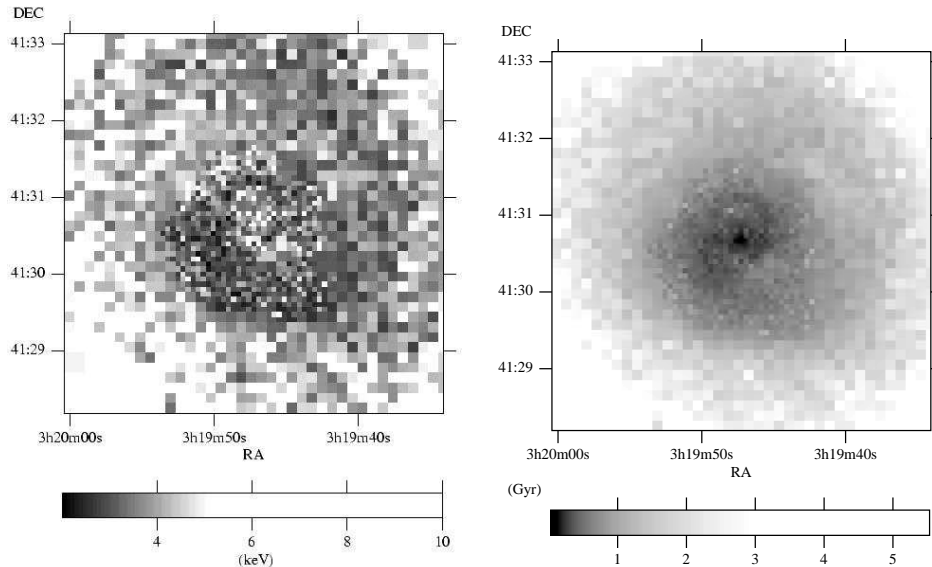


Figure 3. (Left) Temperature and (Right) radiative cooling time maps produced from the X-ray colour ratios (Fabian et al 2000a). Note that the coolest gas ( $T \sim 2.5$  keV) with the shortest cooling time ( $\sim 0.3$  Gyr) lies in the rim around the N lobe and in the E bright blob. Single-phase gas has been assumed for the analysis.

### 2.3. A1795 and A2199

Other clusters with central radio sources which we have observed are A1795 (Fabian et al 2000) and A2199 (Johnstone et al 2001, in preparation). A1795 shows a filament of soft X-ray emission (Fig. 4) which coincides with an optical  $H\alpha$  filament discovered by Cowie et al in 1983. This could be a cooling wake due to motion of the central cluster galaxy. The velocity map of the  $H\alpha$  emission (Hu et al 1985) shows that the wake has the same velocity as the bulk of the cluster (Oegerle & Hill 1994), there is a velocity shift of  $+150 \text{ km s}^{-1}$  at the cD galaxy. The small radio source associated with the cD (Ge & Owen 1993) shows some interaction with the brighter local X-ray emission. A possible X-ray ‘shadow’, a fainter X-ray region, parallel to but further out from the radio lobes, is also seen.

A2199 has large ‘holes’ coincident with its more diffuse outer radio structures (Fig. 5; radio data from Giovannini et al 1998, see also Owen & Eilek 1998) but there is little agreement between the inner radio and X-ray structures. Analysis of the Chandra data on A2199 is in progress (Johnstone et al 2001).

### 2.4. The Virgo cluster and M87

Chandra images of the inner parts of the Virgo cluster around M87 have been made in the ACIS-I detector by Fabian et al (2001 in preparation) and in the ACIS-S detector by Wilson et al (2001). The excess emission along the line of the radio structures, seen in ROSAT data (Bohringer et al 1995), is clearly detected

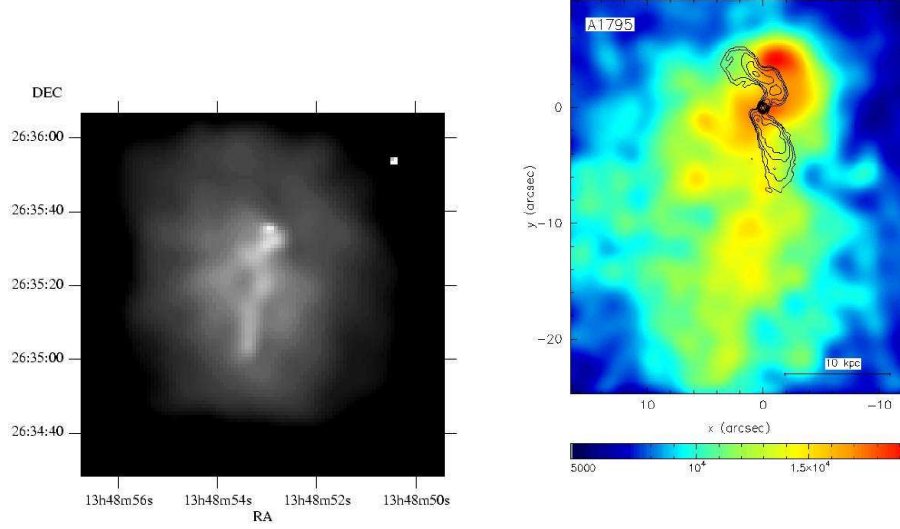


Figure 4. (Left) Adaptively-smoothed X-ray image of the centre of A1795 (Fabian et al 2000). (Right) Overlay of the 3.6 cm radio emission (Ge & Owen 1993) on the X-ray image.

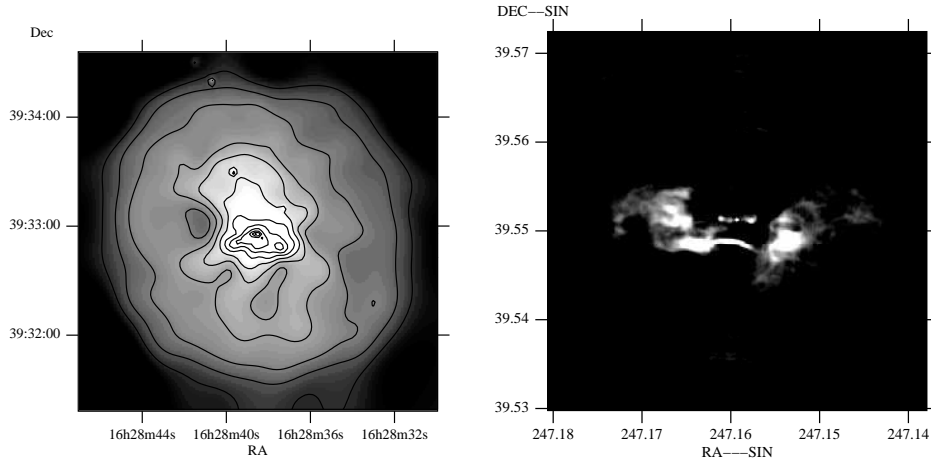


Figure 5. (Left) Adaptively-smoothed 0.5–3 keV X-ray image of the core of A2199 (the contours are logarithmic); (Right) 1.7 GHz radio image (Giovannini et al 1998).

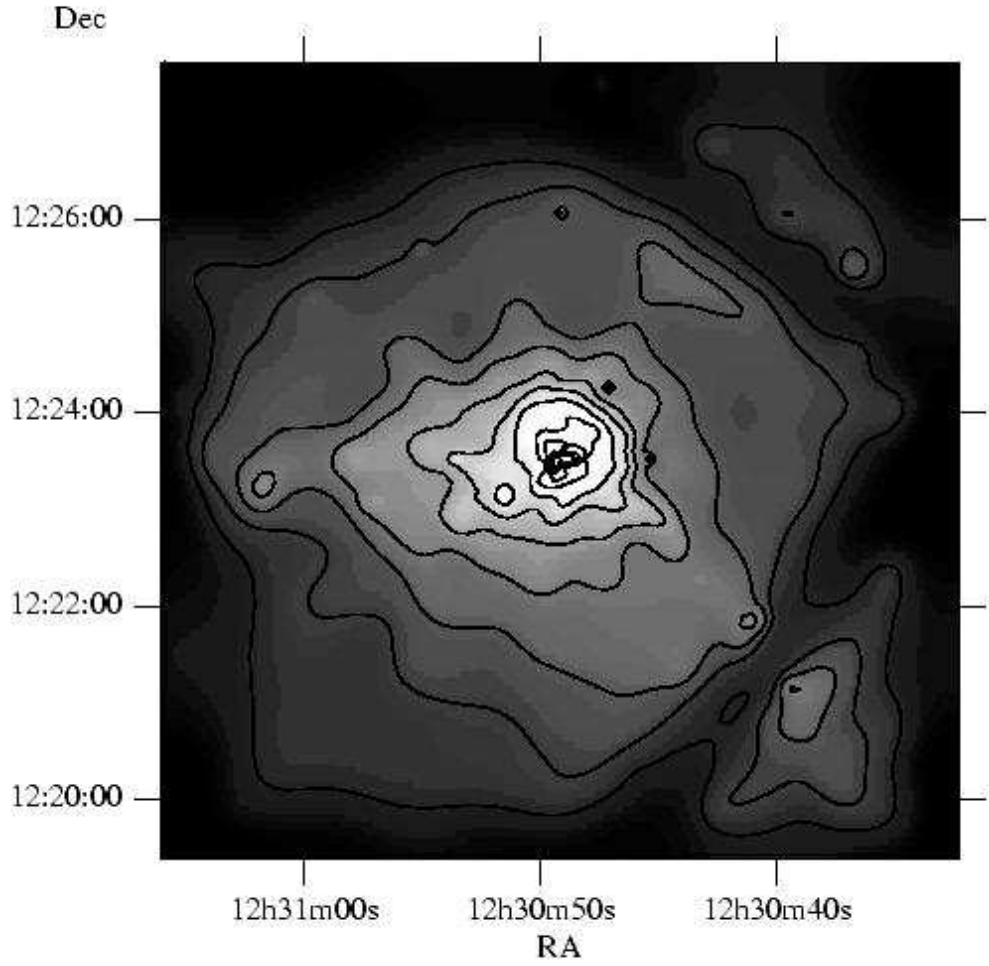


Figure 6. Chandra ACIS-I image (0.5–2.5 keV) of the centre of the Virgo cluster around M87. The dark diagonal structures are due to chip gaps.

(Fig. 6). Only the X-ray structure to the E shows any good correspondence with the radio images (Owen et al 2000). The excess emission there is thermal and cooler than the surrounding gas (Bohringer et al 1995) and possibly due to uplift of cooler gas from nearer the centre by a buoyant radio plume (Bohringer et al 1995; Churazov et al 2000b).

### 3. Summary

The Chandra data so far show little evidence for any widespread steady heating by the radio source. Perhaps there are sporadic upheavals due to large outbursts by the central engine, or a pervasive leakage of energetic particles. Or perhaps cooling dominates.

Conduction may be highly suppressed in cooling flows. Chandran et al (1999) have discussed theoretical possibilities including the mirroring of particles. The Chandra observations of ‘cold fronts’ in some clusters (Markevich et al 2000; Vikhlinin et al 2000) where 5 keV gas lies a few kpc away from 10 keV gas suggests observationally that conduction may in some intracluster regions be highly suppressed (Ettori & Fabian 2000).

### 4. Post-conference appendix

In between the conference and the writing of this paper, Reflection-Grating Spectrometer (RGS) data from XMM have appeared. These have a strong bearing on the appearance of cooling flows so a brief outline of the issues is now given to steer the reader to the relevant literature.

The RGS data of the strong, hot, cooling flow cluster A1835 (Peterson et al 2000) show none of the strong emission lines expected from gas cooling below 3 keV. It seems like the gas cools from about 9 keV down to about 3 keV then vanishes. Similarly there are no lines from gas below about 2 keV from A1795 (Tamura et al 2000) or A1101 (Kaastra et al 2000). The temperature profiles of the gas drop inward in the manner expected from a cooling flow but the spectral signature of the final temperature plunge is missing.

There are many possible explanations, discussed by Peterson et al (2000) and Fabian et al (2000c). Perhaps there is heating. But why then does the gas apparently cool most of the way and is then all heated back up to its original temperature? (It cannot be heated to some other intermediate temperature or it would be detected as accumulating there.) Perhaps the ages of the flows are all only about one Gyr. Perhaps resonance scattering and some absorption operate on the inner, cooler gas making it undetectable. Perhaps the metallicity of the gas is bimodal. A recent paper on M87 by Bohringer et al (2000) shows that the situation is complex, and metallicity, resonance scattering or continuum dilution may be factors. They find that the metallicity gradient in the Virgo cluster in which the iron (and other element) abundance rises inwards reverses in the innermost arcmin resulting in the metallicity going to zero! Not only are no lines seen from cooling gas, but there are no lines from anything else. Clearly further observations, and thought, are required.

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